Not Alone: Tracing the Origins of Very Low Mass Stars and Brown Dwarfs Through Multiplicity Studies

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The properties of multiple stellar systems have long provided important empirical constraints for star formation theories, enabling (along with several other lines of evidence) a concrete, qualitative picture of the birth and early evolution of normal stars. At very low masses (VLM; M $\lesssim$ 0.1 $M_\odot$), down to and below the hydrogen burning minimum mass, our understanding of formation processes is not as clear, with several competing theories now under consideration. One means of testing these theories is through the empirical characterization of VLM multiple systems. Here, we review the results of various VLM multiplicity studies to date. These systems can be generally characterized as closely separated (93% have projected separations $\Delta < 20$ AU) and near equal-mass (77% have $M_2/M_1 \geq 0.8$) occurring infrequently (perhaps 10–30%). Both the frequency and maximum separation of stellar and brown dwarf binaries steadily decrease for lower system masses, suggesting that VLM binary formation and/or evolution may be a mass-dependent process. There is evidence for a fairly rapid decline in the number of loosely-bound systems below $\sim$0.3 $M_\odot$, corresponding to a factor of 10–20 increase in the minimum binding energy of VLM binaries as compared to more massive stellar binaries. This wide-separation "desert" is present among both field ($\sim$1–5 Gyr) and older ($>$ 100 Myr) cluster systems, while the youngest ($\lesssim$10 Myr) VLM binaries, particularly those in nearby, low-density star forming regions, appear to have somewhat different systemic properties. We compare these empirical trends to predictions laid out by current formation theories, and outline future observational studies needed to probe the full parameter space of the lowest mass multiple systems.

1. INTRODUCTION

The frequency of multiple systems and their properties are key constraints for studies of stellar formation and evolution. Binary and multiple stars are common in the Galaxy, and the physical properties of the components in these systems can be significantly influenced by dynamical and coevolutionary processes. Furthermore, successful theories of star formation must take into account the creation of multiples and empirical multiplicity trends as functions of mass, age and metallicity.

The main focus of this review is multiplicity in very low mass (VLM; M $\lesssim$ 0.1 $M_\odot$) stars and brown dwarfs. However, to put these results in the proper context, we start with a brief review of our current understanding of multiplicity among higher mass stars (also see chapter by Duchêne et al.). The standard references for binary frequency are *Duquennoy & Mayor* (1991, hereafter DM91; also *Abt and Levy*, 1976; *Abt*, 1978; *Mayor et al.*, 1992) for solar-type stars and *Fischer and Marcy* (1992, hereafter FM92; also *Henry and McCarthy*, 1990; *Reid and Gizis*, 1997a; *Halbwachs et al.*, 2003; *Delfosse et al.*, 2004) for early-type M

dwarfs. The DM91 survey combined spectroscopic, astrometric and direct imaging of 164 G dwarfs; 44% of those stars were identified as binaries, with incompleteness corrections increasing the binary fraction to $f_{bin} \sim 65\%$. These corrections include 8% attributed to VLM companions; as discussed further below, more recent observations show that the actual correction is much lower. The FM92 survey covered 72 M2-M5 dwarfs within 20 parsecs, and derived $f_{bin} = 42 \pm 9\%$, significantly lower than the DM91 G-dwarf survey. While both surveys include nearby stars, neither comprises a *volume-complete* sample.

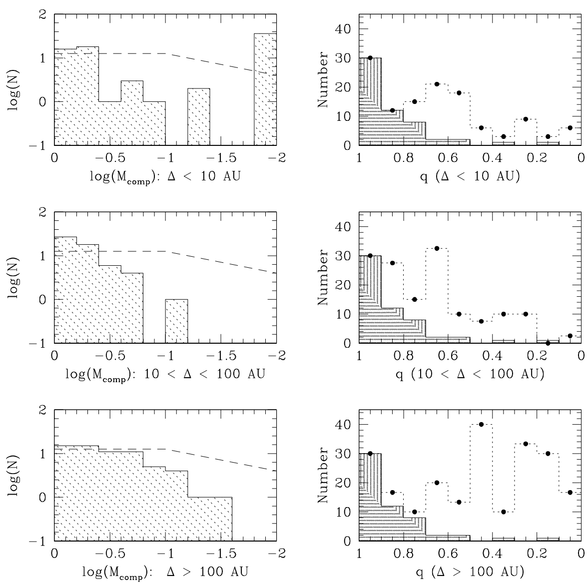

Fig. 1.— Mass and mass ratio distributions of companions to late-F to K-type dwarfs within 25 parsecs of the Sun (*Reid et al.*, 2002a), segregated by projected separation/orbital semimajor axis. The left panels plot the mass distribution of companions, with the dashed lines providing a schematic representation of the initial mass function. The right panels plot the mass-ratio distributions (dotted histograms), with the solid histogram showing the mass ratio distribution for VLM dwarfs (no segregation of separations; see Fig. 3). These distributions are normalized at the $q = 1$ bin.

Recent surveys of solar-type stars have concentrated on VLM companions. Radial velocity (RV) surveys (e.g., *Marcy and Butler*, 2000; *Udry et al.*, 2003) have shown that less than 0.5% of solar-type stars have brown dwarf companions within ~ 5 AU. *Guenther et al.* (2005) find $f_{bin}^{BD} < 2\%$ for projected separations $\Delta < 8$ AU among Hyades stars; this is in contrast with $f_{bin} \sim 13\%$ for stellar-mass companions at those separations (DM91). At larger separations, imaging surveys of young Solar neighborhood stars (members of the TW Hydrae, Tucanae, Horologium and β Pic associations; *Zuckerman and Song*, 2004) find $f_{bin}^{BD} \sim 6 \pm 4\%$ for $\Delta > 50$ AU (*Neuhäuser et al.* 2003), similar to the brown dwarf companion fraction measured for field stars for separations of 30–1600 AU (*Metchev*, 2005). These fractions are ~3 times lower than the hydrogen-burning companion rate over the same separation range. At the widest separations ($\Delta > 1000$ AU), *Gizis et al.* (2001) find that solar-type stars have comparable numbers of brown dwarf and M dwarf companions, although this result is based on a very small number of VLM companions.

Besides the overall binary fraction, the mass distribution of companions sets constraints on formation models. Fig. 1 shows the results for late-F to K stars ($0.5 < (B-V) < 1.0$) within 25 parsecs of the Sun, breaking down the sample by projected separation/orbital semi-major axis. The left panels compare the mass distribution of companions against a schematic representation of the initial mass function (*Reid et al.*, 1999, 2002a); the right panels compare the mass ratio ($q \equiv M_2/M_1$) distributions against the VLM dwarf data assembled in this review (cf., Fig. 3). Clearly, low q binary systems are more common at all separations among solar- type stars than in VLM dwarfs. We return to this issue in Section 2.2.3. At small separations ($\Delta < 10$ AU), there is an obvious deficit of low-mass companions (with the exception of planetary companions) as compared to the distribution expected for random selection from the field-star mass function. The notorious brown dwarf desert (e.g., *Marcy and Butler*, 2000) extends well into the M dwarf regime. This result is consistent with the original analysis of *Mazeh and Goldberg* (1992) of the mass ratio distribution of spectroscopic binaries, although their more recent study of proper motion stars (*Goldberg et al.*, 2003) finds a bimodal distribution, with peaks at q ~0.8 and ~0.2 (see also *Halbwachs et al.*, 2003). The deficit in low-mass companions is less pronounced at intermediate separations, while it is possible that observational selection effects (e.g., sensitivity limitations) might account for the small discrepancy for $q < 0.2$ in the wide-binary sample.

In the case of M dwarfs, attention has focused on the nearest stars. *Delfosse et al.* (2004) recently completed a spectroscopic and adaptive optics (AO) imaging survey of M dwarfs within 9 parsecs that is effectively complete for stellar mass companions. Combining their results with the imaging surveys by *Oppenheimer et al.* (2001) and *Hinz et al.* (2002), they derive an overall binary fraction of 26% for M dwarfs. For a more detailed breakdown with spectral type, we can turn to the northern 8-parsec sample (*Reid and Gizis*, 1997a; *Reid et al.*, 2003). Those data indicate binary fractions of 24^{+13}_{-7}% for spectral types M0-M2.5 (4/17 systems), 27^{+5}_{-7}% for M3-M4.5 (12/45 systems) and 31^{+13}_{-9}% for M5-M9 (5/16 systems; uncertainties assume a binomial distribution), where the spectral type refers to the primary star in the system; the overall binary frequency is $f_{bin} = 27^{+5}_{-4}\%$. These results, based on volume-limited samples, confirm that M dwarfs have significantly lower multiplicity than more massive solar-type stars.[1] This is

[1] Even with 30% binarity for M dwarfs, most stars still reside in multiple systems. As a numerical example, consider a volume-limited sample of 100 stellar systems: 20 are type G or earlier, 10 are type K and 70 are type M. Assuming binary fractions of 70%, 50% and 30%, respectively, these

consistent with an overall trend of decreasing multiplicity with decreasing mass (cf., A- and B-stars have overall multiplicity fractions as high as 80%; *Shatsky and Tokovinin*, 2002; *Kouwenhoven et al.*, 2005). These changes in multiplicity properties with mass among hydrogen-burning stars emphasize that we must consider VLM dwarfs as part of a continuum, not as a distinct species unto themselves.

2. OBSERVATIONS OF VERY LOW MASS BINARIES

2.1 Very Low Mass Binary Systems

With the discovery of hundreds of VLM dwarf stars and brown dwarfs over the past decade (see reviews by *Basri*, 2000; *Oppenheimer et al.*, 2000; and *Kirkpatrick*, 2005), it is now possible to examine systems with primaries down to 100 times less massive than the Sun. In this regime, formation mechanisms are under considerable debate (see chapters by Bonnell et al., Goodwin et al., Klein et al., Luhman et al., and Whitworth et al.). Hence, accurate assessment of the multiplicity and systemic properties of VLM stars and brown dwarfs are essential for constraining current theoretical work.

Searches for VLM binaries — defined here as having a total system mass M$_{tot}$ $<$ 0.2 M$_\odot$ and primary mass M$_1$ $<$ 0.1 M$_\odot$ (cf., *Siegler et al.*, 2005) — have been conducted predominantly through high resolution imaging surveys, using both ground-based (including natural and, quite recently, laser guide star adaptive optics [AO]) and space-based facilities. Major surveys have targetted both nearby field sources (*Koerner et al.*, 1999; *Reid et al.*, 2001; *Bouy et al.*, 2003; *Burgasser et al.*, 2003; *Close et al.*, 2002, 2003; *Gizis et al.*, 2003; *Siegler et al.*, 2003, 2005; *Law et al.*, 2006; *Allen et al.* in preparation; *Billères et al.* in preparation; *Burgasser et al.* in preparation; *Reid et al.* in preparation) and young clusters and associations (*Martín et al.*, 1998, 2000a, 2003; *Neuhaüser et al.*, 2002; *Kraus et al.*, 2005; *Luhman et al.*, 2005; *Bouy et al.*, 2006). A smaller number of high resolution spectroscopic surveys for closely separated binaries have also taken place (*Basri and Martín*, 1999; *Joergens and Guenther*, 2001; *Reid et al.*, 2002b; *Guenther and Wuchterl*, 2003; *Kenyon et al.*, 2005; *Joergens*, 2006). Only one eclipsing system has been discovered so far via photometric monitoring (*Stassun et al.*, 2006). Observations leading to the identification of low mass multiple systems has been accompanied by resolved photometry and spectroscopy, allowing characterization of the colors, luminosities and spectral characteristics of several binary components. Astrometric and radial velocity monitoring has lead to mass measurements or constraints for five VLM systems to date (*Basri and Martín*, 1999; *Lane et al.*, 2001b; *Bouy et al.*, 2004a, *Brandner et al.*, 2004; *Zapatero Osorio et al.*, 2004; *Stassun et al.*, 2006).

100 systems include 140 stars, 80 in binaries and 60 in isolated systems. Higher order multiples only serves to increase the companion fraction.

In Table 1 we list 75 VLM binary systems published in the literature or reported to us as of 2005. The mass criteria correspond to field dwarf binary components later than spectral type ∼M6; younger systems may include earlier spectral types. Table 1 provides a subset of the compiled data for these sources, given in more complete detail through an online database maintained by N. Siegler (See http://paperclip.as.arizona.edu/∼nsiegler/VLM_binaries.).

2.2 General Properties of VLM Binaries

Large-scale, high resolution imaging surveys in the field have converged to similar conclusions on the general properties of VLM field binaries. Compared to their higher mass stellar counterparts, VLM binaries are

- rarer ($f_{bin} \approx 10-30$%; however, see discussion below);
- more closely separated (93% have $\Delta < 20$ AU);
- and more frequently in near-equal mass configurations (77% have $q \geq 0.8$).

Analogous imaging surveys in young open clusters (e.g., Pleiades, α Persei) find similar trends, although the youngest ($\lesssim$10 Myr) associations (e.g., Chamaeleon I, Upper Scorpius, Orion) appear to exhibit somewhat different properties. We discuss these broad characterizations in detail below.

2.2.1 The Binary Fraction

Magnitude-limited imaging surveys for VLM stars and brown dwarfs in the field with spectral types M6 and later have generally yielded *observed* binary fractions of ∼20%; taking into consideration selection effects (e.g., *Burgasser et al.*, 2003) lowers this fraction to 7–15% for $\Delta \gtrsim 2-3$ AU and $q \gtrsim$ 0.4–0.5 (*Bouy et al.*, 2003; *Burgasser et al* 2003; *Close et al.*, 2003; *Siegler et al.*, 2005). *Burgasser et al.* (2003) deduced $f_{bin} = 9^{+11}_{-4}$% for a small sample of L and T dwarfs using the $1/V_{max}$ technique (*Schmidt et al.*, 1968); *Bouy et al.* (2003) deduced a volume-limited fraction of $f_{bin} \sim 15$%. Over the same separation ($\Delta > 2$ AU) and mass ratio ($q > 0.5$) ranges, these multiplicity rates are less than half of those of M dwarfs (FM92; *Close et al.*, 2003) and G dwarfs (DM91; *Bouy et al.*, 2003). Similarly, HST imaging surveys of the 125 Myr Pleiades open cluster (*Martín et al.*, 2000a, 2003; *Bouy et al.*, 2006) found a resolved binary fraction of 13–15% for $\Delta > 7$ AU for components at and below the hydrogen burning limit. On the other hand, *Kraus et al.* (2005) found f_{bin} = 25$^{+16}_{-8}$% for a small sample of 0.04–0.1 M$_\odot$ members of Upper Scorpius over the range Δ = 5–18 AU, somewhat higher than, but still consistent with, other field and open cluster results.

One problem with resolved imaging surveys is their inherent selection against tightly bound systems ($\Delta \lesssim 2-3$ AU for the field dwarfs and nearby associations,

$\Delta \lesssim 10 - 15$ AU for more distant star forming regions). Here, one must generally turn to high resolution spectroscopic surveys of VLM stars, currently few in number and with as yet limited follow-up. *Reid et al.* (2002b) deduced a double-lined spectroscopic binary (SB2) fraction of 6^{+7}_{-2}% for a sample of M7-M9.5 field dwarfs. *Guenther and Wuchterl* (2003) identified two SB2s and marginally significant RV variations in the active M9 LP 944-20 (which they attribute to either the presence of a low-mass companion or magnetic-induced activity) in a sample of 25 M5.5-L1.5 field and cluster dwarfs. Including all three objects implies an observed binary fraction of 12^{+10}_{-4}%, although this value does not take into consideration selection biases. *Joergens* (2006) detected one RV variable, the M6.5 Cha Hα8, among a sample of 9 VLM stars and brown dwarfs in the 2 Myr Cha I association, implying an observed fraction of 11^{+18}_{-4}%, again subject to sampling and selection biases. *Kenyon et al.* (2005) identified four possible spectroscopic binaries (SBs) among VLM stars and brown dwarfs in the 3-7 Myr σ Orionis cluster on the basis of RV variations over two nights. They derive $f_{bin} > 7 - 17\%$ for $\Delta < 1$ AU (after correcting for selection effects) and a best-fit fraction of 7–19% (for their Sample A) depending on the assumed underlying separation distribution. However, none of the sources from this particular study have had sufficient follow up to verify RV variability, and cluster membership for some of the targets have been called into question. A more thorough analysis of sensitivity and sampling biases in these SB studies has been done by *Maxted and Jeffries* (2005), who find f_{bin} = 17–30% for $\Delta < 2.6$ AU, and an overall binary fraction of 32–45% (assuming f_{bin} = 15% for $\Delta > 2.6$ AU). This result suggests that imaging studies may be missing a significant fraction of VLM systems hiding in tightly-separated pairs. However, as orbital properties have only been determined for two SB systems so far (PPl 15, *Basri and Martín*, 1999; and 2MASS 0535-0546, *Stassun et al.*, 2006), individual separations and mass ratios for most VLM SB binaries remain largely unconstrained.

Two recent studies (*Pinfield et al.*, 2003; *Chapelle et al.*, 2005) have examined the fraction of unresolved (overluminous) binary candidates among VLM stars and brown dwarfs in young associations. Contrary to other studies, these groups find much larger binary fractions, as high as 50% in the *Pinfield et al.* study of the Pleiades and Praesepe for $q > 0.65$. This study also finds a binary fraction that increases with decreasing mass, in disagreement with results in the field (see below); the *Chapelle et al.* study finds evidence for the opposite effect in the 0.9 Gyr Praesepe cluster. Both studies have been controversial due to the lack of membership confirmation, and hence likelihood of contamination; and the possible influence of variability on the identification of overluminous sources. Nevertheless, both of these studies and the SB results suggest that a higher VLM binary fraction than that inferred from imaging studies, perhaps 30% or more, is possible.

2.2.2 The Separation Distribution

Fig. 2 plots the histogram of projected separations/orbital semimajor axes for 70 binaries in Table 1 (SB systems without orbital measurements are not included). This distribution exhibits a clear peak around 3–10 AU, with 53$\pm$6% of known VLM binaries encompassing this range. Again, because imaging surveys (from which most of the objects in Table 1 are drawn) can only resolve systems down to a minimum angular scale (typically $0\farcs05 - 0\farcs1$ for AO and HST programs), the decline in this distribution at small separations is likely a selection effect. Results from SB studies remain as yet unclear in this regime. *Basri and Martín* (1999) have suggested that very close binaries are common based on the detection of one (PPl 15) in a small spectral sample The analysis of *Maxted and Jeffries* (2005) suggest that there may be as many or more binaries with $\Delta \lesssim 3$ AU as those with $\Delta \gtrsim 3$ AU. At the extreme, *Pinfield et al.* (2003) estimate that 70–80% of VLM binaries in the Pleiades have $\Delta < 1$ AU, although this result has not been corroborated by similar studies in the Pleiades (*Bouy et al.*, 2006) and Praesepe (*Chapelle et al.*, 2005). In any case, as the peak of the observed separation distribution lies adjacent to the incompleteness limit, closely separated systems likely comprise a non-negligible fraction of VLM binaries.

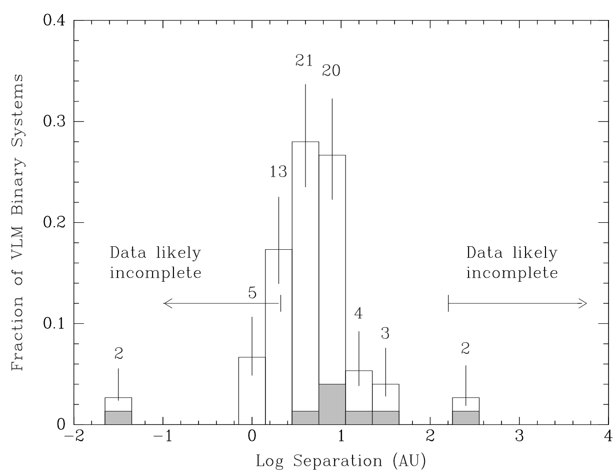

Fig. 2.— Distribution of separations/orbital semimajor axes for known VLM binary systems (Table 1). The number of VLM binary systems in each 0.3 dex bin is labelled, and uncertainties (vertical lines) are derived from a binomial distribution. Note that SBs with unknown separations are not plotted but included in the total number of binaries for scaling the distribution. The distribution peaks at $\Delta \sim 3 - 10$ AU, with steep declines at shorter and longer separations. While there is likely observational incompleteness for $\Delta \lesssim 3$ AU, the sharp drop in binary systems with $\Delta \gtrsim 20$ AU is a real, statistically robust feature. The shaded bins represent the 8 systems with ages < 10 Myr. While the statistics are still small, the separation distribution of these young binaries is flatter, and suggests a peak at wider separations than that of the field and older cluster binaries.

The steep decline in the separation distribution at larger

separations is, on the other hand, a statistically robust feature. While high resolution imaging surveys are limited in this domain by field of view (typically 10–20″ for HST and AO studies), this only excludes systems with $\Delta \gtrsim 150$ AU for a typical VLM field source (distances $\sim$ 30 pc) or $\Delta \gtrsim 200 - 1000$ AU for young cluster systems. Even wider separations for hundreds of VLM field dwarfs should be detectable – and are not found – in the original surveys from which they were identified (e.g., 2MASS, DENIS and SDSS; however, see *Billères et al.*, 2005). In open clusters, deep imaging has demonstrated a consistent lack of wide companions to VLM dwarfs. An upper limit of $f_{bin} < 8\%$ for $\Delta > 11$ AU is derived for the 90 Myr α Per open cluster (*Martín et al.*, 2003), similar to the 5% upper limit for $\Delta > 15$ AU measured for 32 VLM members of the 2 Myr IC 348 cluster (*Luhman et al.*, 2005). *Lucas et al.* (2005) measure an upper limit of 2% for wide VLM binaries ($\Delta > 150$ AU) in the 1 Myr Trapezium cluster based on a two-point correlation function. In contrast, 93% of the known VLM binaries have $\Delta \lesssim 20$ AU. Hence, a "wide brown dwarf binary desert" is evidenced for VLM stars and brown dwarfs (*Martín et al.*, 2000a), a potential clue to their formation.

While survey results have generally been negative for wide VLM binaries, two — 2MASS J11011926-7732383AB (*Luhman*, 2004; hereafter 2MASS 1101-7732AB) and DENIS J055146.0-443412.2AB (*Billères et al.*, 2005, hereafter DENIS 0551-4434AB) – have been identified serendipitously. These systems have projected separations $\gtrsim 200$ AU, over 10 times wider than the vast majority of VLM binary systems. A third low mass binary not included in Table 1, GG Tau BaBb (a.k.a. GG Tau/c; *Leinert et al.*, 1991; *White et al.*, 1999), with estimated primary and total system masses of 0.12 and 0.16 $M_{\odot}$, respectively, also has a projected separation greater than 200 AU. Interestingly, two of these three systems are members of very young, loose associations. We discuss these source further in §2.4.2.

The separation distribution of VLM stars therefore peaks at or below ~3–10 AU, corresponding to orbital periods of $\lesssim$40 yr. This is quite different from the separation distribution of G dwarfs, which shows a broad peak around 30 AU (periods of ~170 yr; DM91); and the M dwarf distribution, which peaks between 4–30 AU (periods of 9–270 yr; FM92). There is a suggestion in this trend of decreasing separations as a function of mass, as discussed further below.

2.2.3 The Mass Ratio Distribution

Fig. 3 shows the distribution of mass ratios for 70 of the binaries in Table 1 (not including SBs without mass estimates). These ratios were derived by a variety of methods, including comparison of component fluxes to evolutionary models (e.g., *Chabrier et al.*, 2000), analytic relations (e.g., *Burrows et al.*, 2001) and direct estimates from orbital motion measurements. Despite these different techniques, a comparison of all the data shows congruence with individual studies. The mass ratio distribution for VLM systems is strongly peaked at near-unity ratios; over half of the known VLM binaries have $q > 0.9$ and $77^{+4}_{-5}\%$ have $q \geq 0.8$.

As with the separation distribution, it is important to consider selection effects in the observed mass ratios. Most pertinent is the detectability of secondaries in low q binaries, which may be too faint for direct imaging or of insufficient mass to induce a measureable RV variation in the primary's spectrum. The former case is an important issue for field binaries, as low mass substellar companions fade to obscurity over time. However, most imaging and spectroscopic surveys to date are sensitive down to $q \gtrsim 0.5$, while a sharp dropoff is clearly evident at the highest mass ratios. Hence, while the number of low mass ratio systems may be underestimated, the $q \sim 1$ peak is not the result of this bias.

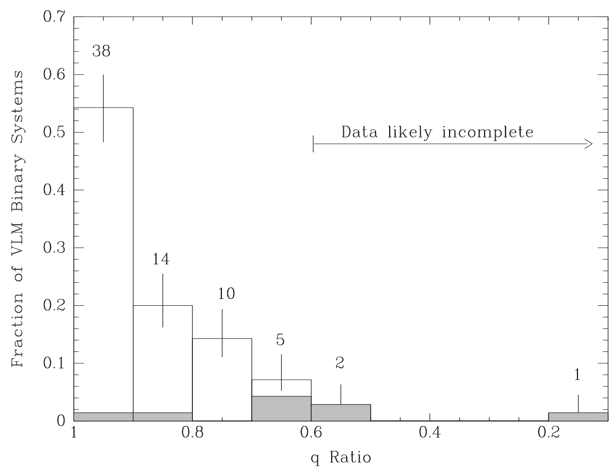

Fig. 3.— Mass ratio distribution of known VLM binary systems (Table 1). The number of VLM binary systems in each 0.1 fractional bin is labelled, and uncertainties are derived from a binomial distribution. Note that SBs with unknown mass ratios are not plotted and not included in the total number of binaries when scaling the distribution. The distribution peaks near unity for binary systems with $\Delta \gtrsim 3 - 4$ AU, and matches a power law. Note that incompleteness is likely for $q \lesssim 0.6$. The shaded bins represent the eight systems with ages < 10 Myr. While the statistics are still small, the mass ratio distribution of these young systems suggests a flatter distribution than that of field and older cluster binaries.

A second effect is the preferential discovery of unresolved equal-mass systems in wide field surveys. As such systems are twice as bright as their single counterparts, they are ~3 times more likely to be found than single sources in a magnitude-limited survey. Systems with lower mass ratios are not as overluminous and less affected by this bias. *Burgasser et al.* (2003) examined this impact of this bias on a small sample of L and T dwarf binaries and found it to be significant only for $q \lesssim 0.6$. Hence, this bias cannot be responsible for the $q \sim 1$ peak.

VLM (field and open cluster) binaries therefore show a

clear preference for equal mass systems, in contrast to the majority of F–K stellar systems (Fig. 1). It is worth noting that M dwarfs in the 8 pc sample show a similar, although less pronounced, $q \sim 1$ peak (*Reid and Gizis*, 1997a), again suggesting a mass-dependent trend.

2.2.4 Higher Order Multiples

Thus far we have focused on VLM binaries, but higher order multiples (triples, quadruples, etc.) are also abundant among more massive stars, comprising perhaps 15–25% of all multiple stellar systems (*Tokovinin*, 2004; see chapter by Duchêne et al.). Several VLM binaries are components of higher order multiple systems with more massive stars. *Burgasser et al.* (2005a) have even suggested a higher binary fraction for brown dwarfs that are widely-separated companions to massive stars. Higher order multiples are currently rare among purely VLM systems, however. The LP 213-67/LP 213-68AB system is one exception, with the three components (spectral types M6.5, M8 and L0) forming a wide hierarchical triple with separations of 340 AU and 2.8 AU (*Gizis et al.*, 2000a; *Close et al.*, 2003). DENIS 0205-1159AB may also have a third component, marginally resolved through high resolution imaging (*Bouy et al.*, 2005). Considering both systems as VLM triples, the ratio of high-order multiples to binaries is only 3^{+4}_{-1}%, quite low in comparison to higher mass stars. This may be due to selection effects, however, as the already tight separations of VLM binaries implies that the third component of a (stable) hierarchical triple must be squeezed into an extremely small orbit. Indeed, this could argue against a large fraction of higher order VLM systems. On the other hand, undiscovered wide tertiaries (as in LP 213-67/LP 213-68AB) may be present around some of these systems. Additional observational work is needed to determine whether higher order VLM multiples are truly less common than their stellar counterparts.

2.3 Statistical Analysis: Bayesian Modeling

To examine the observed binary properties of resolved VLM stars in more detail, we performed a Bayesian statistical analysis of imaging surveys to date. The Bayesian approach allows the incorporation of many disparate data sets, and the easy assimilation of non-detections, into a unified analysis of a single problem (*Sivia*, 1996). We focused our analysis on the surveys of *Koerner et al.* (1999); *Reid et al.* (2001); *Bouy et al.* (2003); *Close et al.* (2003); *Gizis et al.* (2003); *Siegler et al.* (2005); and *Allen et al.* (in preparation). The Bayesian statistical method employed is similar to that described in *Allen et al.* (2005).

We first constructed a set of parameterized companion distribution models in terms of orbital semi-major axis (a) and companion mass ratio. For the semi-major axis distribution we use a Gaussian in log AU given by:

$$P(a_0, \sigma_a) = \frac{1}{\sqrt{2\sigma_a{}^2}} e^{-(\log(a)-\log(a_0))^2/2\sigma_a^2} \qquad (1)$$

where a_0 is the peak of the Gaussian and σ_a is the logarithmic half-width, both variable parameters. This formulation is prompted by the results of DM91 and FM92 (however, see *Maxted and Jeffries*, 2005). For the mass-ratio model, we assume a power law of the form:

$$P(N, \gamma) = N \frac{q^\gamma}{\int_0^1 q^\gamma} \qquad (2)$$

where the normalization factor N is defined to be the overall binary fraction (i.e., f_{bin}), and γ is a variable parameter.

In order to compare the model distributions to the data, we transform them to observables, namely the log of the projected separation ($\log \Delta$) and the difference in magnitude between the secondary and the primary (ΔM). The former is computed by transforming the semi-major axis distribution as:

$$\Delta = a\sqrt{cos^2(\phi)sin^2(i) + sin^2(\phi)}, \qquad (3)$$

where we assume a uniform distribution of circular orbits over all possible inclinations (i) and phases (ϕ). The transformation of the q distribution to a ΔM distribution is done by assigning each mass ratio a range of possible luminosities for ages between 10 Myr and 10 Gyr using evolutionary models from *Burrows et al.* (2001).

The transformed model distributions are then compared to the observed distributions via a Bayesian statistical method, as described in *Allen et al.* (2005). The models are directly compared to the data after being convolved with a window function, which describes how many times a bin in observational space (Δ, ΔM) was observed in a particular survey. In this way we do not analyze the models where there is no data, and the relative frequency of observations is taken into account.

The output posterior distribution is four dimensional ($\log(a_0)$, σ_a, N, γ) and is impossible to display in its entirety. Instead, we show marginalized distributions (Fig. 4), collapsing the posterior distribution along different parameter axes. These distributions have a non-negligible dispersion, as parameters spaces outside the observational window function (e.g., very tight binaries) add considerable uncertainty to the statistical model. Nevertheless, the distributions are well-behaved and enable us to derive best-fit values and uncertainties for the various parameters. The overall binary fraction is reasonably well constrained, $N = 22^{+8}_{-4}$%, with a long tail in its probability distribution to higher rates. The remaining parameters are $\log(a_0) = 0.86^{+0.06}_{-0.18}\ \log(AU)$, $\sigma_a = 0.24^{+0.08}_{-0.06}\ \log(AU)$, and $\gamma = 4.8^{+1.4}_{-1.6}$ (all listed uncertainties are 68% confidence level).

The mass ratio and projected separation distributions inferred from the best-fit parameters are shown in Fig. 5. The best-fit binary fraction is 22%, but after applying our window function the expected resolved fraction is $\sim$17%, slightly higher than but consistent with the observed f_{bin} from imaging surveys (§ 2.2.1). The best-fit mass ratio distribution is highly peaked near q = 1, similar to the data

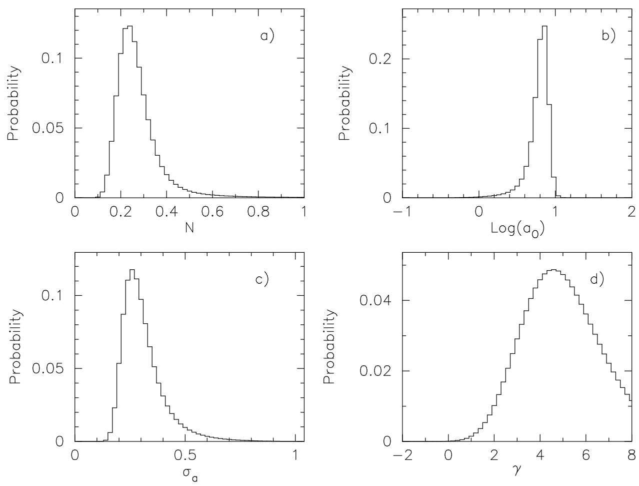

Fig. 4.— Posterior probability distributions of the four companion model parameters: a) overall binary fraction (N); b) center of the semi-major axis distribution ($\log(a_0)$); c) width of the semi-major axis distribution (σ_a); d) mass ratio distribution power law index (γ).

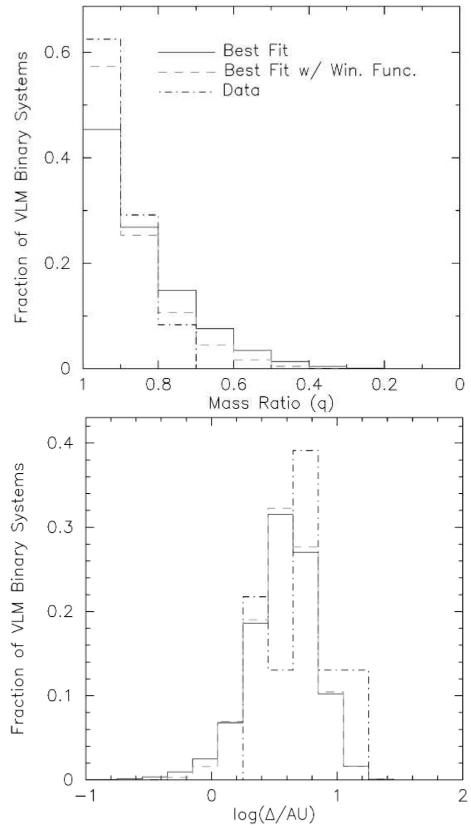

Fig. 5.— *(Top)* The fraction of VLM binaries with a given q for the best fit model (solid line), the best fit model view through the window function (dashed line), and the data used in the Bayesian analysis (dot-dashed line). Note how the window function over-emphasizes the high mass ratio systems. *(Bottom)* The projected separation distribution for the best fit model (lines are the same as the top panel).

but somewhat flatter than observed due to selection effects in the empirical samples. This nevertheless confirms that the mass ratio distribution is fundamentally peaked towards high q values.

The best fit value for the peak of the semimajor axis distribution is ~7 AU, implying a peak in the projected separation distribution of about 3.5 AU, matching well with the data (Fig. 5b). The best fit width of this distribution is quite narrow, implying very few wide systems ($> 20\ AU \sim 1\%$) and very few close systems (< 1 AU $\sim$ 2-3%). It is important to stress that the imaging data provide weak constraints on closely-separated binaries, and the latter fraction may be somewhat higher (cf., *Maxted and Jeffries*, 2005). On the other hand, the constraint on the wide binary fraction (1% or less) is the most robust result of this analysis. Between all of the surveys considered here there are over 250 unique fields that have been probed for companions out to hundreds of AU with no detections. Hence, such pairings are exceptionally rare.

2.4 Discussion

2.4.1 On the Preference of Tight Binaries

The sharp decline in the VLM binary fraction for $\Delta >$ 20 AU is not a feature shared with more massive stellar systems, which can extend from 0.1 AU to 0.1 pc. However, the decline is consistent with the observed trend of smaller mean separations, and smaller maximum separations, from A to M field binaries. This is demonstrated in Fig. 6, which plots projected separations/semimajor axes versus total system mass for stellar and substellar field and cluster binaries. The maximum separations (Δ_{max}) of these systems show a striking dependence on total system mass. Prior to the discovery of the wide pairs 2MASS 1101-7732AB and DENIS 0551-4434AB, *Burgasser et al* (2003) found a power-law relation between Δ_{max} and total system mass, Δ_{max} = 1400($M_{tot}/M_\odot)^2$ AU, that appeared to fit all VLM systems known at that time. Similarly, *Close et al.* (2003) found a linear relation of Δ_{max} = 23.2(M_{tot}/0.185 $M_\odot$) AU for VLM binaries, corresponding to a minimum escape velocity V_{esc} = 3.8 km s^{-1}. This was greater than a minimum value of V_{esc} = 0.6 km s^{-1} inferred for more massive stellar systems, and both results indicate that lower mass binaries are progressively more tightly bound. *Close et al.* (2003) further pointed out a possible "break" in the minimum binding energies of stellar and VLM binaries, also shown in Fig. 6. Around $M_{tot} \approx 0.3\ M_\odot$, the majority of wide VLM systems appear to be 10–20 times more strongly bound than the widest stellar systems.

More recently, exceptions to the empirical trends shown in Fig. 6 have been identified, including the widely-separated VLM systems 2MASS 1101-7732AB, DE-

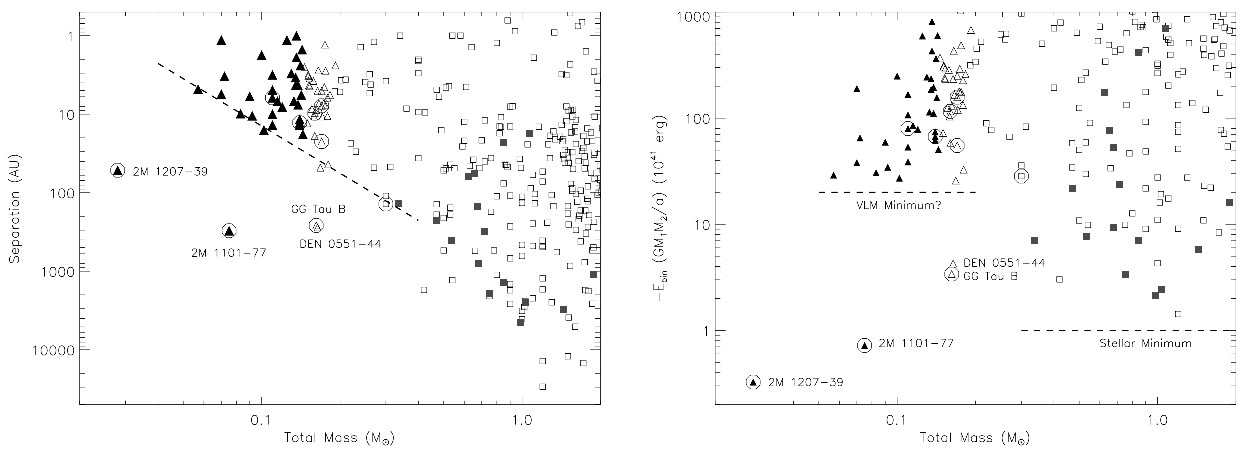

Fig. 6.— *(Left)* Separation (in AU) versus total system mass (in Solar masses) for known binary systems. Stellar binaries from *Close et al.* (1990); DM91; FM92; *Reid and Gizis*, (1997b); and *Tokovinin*, (1997) are shown as open squares; stellar-brown dwarf systems compiled by *Reid et al.* (2001) are shown as filled squares. The 68 binaries from Table 1 with measured projected separations and estimated masses are plotted as triangles; filled triangles indicate substellar primaries. Systems younger than 10 Myr are encircled. The dotted line indicates the maximum separation/system mass relation for VLM stellar and substellar binaries proposed by *Burgasser et al.* (2003), indicating that lower mass systems are more tightly bound (see also *Close et al.*, 2003). However, three young systems (GG Tau BaBb, 2MASS 1101-7732AB and 2MASS 1207-3932AB), and the field binary DENIS 0551-4434AB, all appear to contradict these trends. *(Right)* Same systems but this time comparing binding energy ($-E_{bind} = G\mathrm{M}_1\mathrm{M}_2/a$) to total system mass. As first pointed out in *Close et al.* (2003), the widest VLM field binaries are 10–20 times more tightly bound than the widest stellar binaries, with the singular exception of DENIS 0551-4434AB. On the other hand, the three young VLM systems GG Tau BaBb, 2MASS 1101-7732AB and 2MASS 1207-3932AB are much more weakly bound.

NIS 0551-4434AB and GG Tau BaBb. In addition, the extremely low mass ($\mathrm{M}_{tot} \approx 0.03\ \mathrm{M}_\odot$) brown dwarf pair 2MASS J12073346-3932549AB (*Chauvin et al.*, 2004, 2005a; hereafter 2MASS 1207-3932AB), identified in the 8 Myr TW Hydrae moving group (*Gizis*, 2002), falls well outside the mass/Δ_{max} limits outlined above. Such “exceptions” have called into question whether current empirical separation limits are representative of VLM systems in general, and can be considered robust constraints for formation models; or if wide binaries are a normal (if rare) mode of VLM binary formation. These questions remain under debate.

2.4.2 Do Evolution or Environment Play a Role in VLM Binary Properties?

That three of the four weakly bound VLM systems are in young ($\lesssim$10 Myr), low density associations may be an important clue to their formation and existence, and encourages a closer examination of the multiplicity properties of such objects in general. The shaded histograms in Figs. 2 and 3 delineate the separation and mass ratio distributions, respectively, of the 8 binaries in Table 1 that are members of clusters or associations younger than 10 Myr. These distributions, although based on small number statistics, are nevertheless compelling. Young systems show a much broader range of separations, spanning 0.04 $\lesssim \Delta \lesssim$ 240 AU, with 25^{+19}_{-9}% (2/8) having $\Delta > 20$ AU (as compared to 5^{+4}_{-1}% of older VLM systems). The mass ratio distribution is also quite flat, with a *statistically significant* shortfall in the relative number of $q \geq 0.8$ binaries (25^{+19}_{-9}% versus 81^{+4}_{-6}%). Assuming that the older field sources predominately originate from young clusters (*Lada and Lada*, 2003), these differences suggest an *evolution* of VLM binary properties over a timescale of 5–10 Myr.

However, care must be taken when interpreting these data, as selection effects can distort the underlying distributions. Because the youngest brown dwarfs are still quite warm and luminous, imaging surveys in young clusters can generally probe much smaller masses — and hence smaller mass ratios — than equivalent surveys of older clusters or in the field. In addition, with the exception of some nearby moving groups (e.g., TW Hydra, Ursa Major), most of the youngest clusters lie at larger distances, so closely separated systems ($\Delta \lesssim 10$ AU) cannot be generally resolved through direct imaging. This biases young samples against the close separations typical of field binaries. So in fact there may be many more closely-separated young VLM pairs, or many more widely-separated, small mass ratio older VLM pairs, than currently known.

What about older VLM members of the Galactic thick disk and halo? Unfortunately, current imaging searches for companions to low-mass subdwarfs are not yet capable of detecting substellar companions directly, and radial velocity surveys of the necessary frequency are not yet complete.

Gizis and Reid (2000) imaged nine VLM metal-poor (M subdwarf) primaries with HST, and found that none had companions down to the hydrogen-burning limit. This sample has been extended to a total of 28 M subdwarfs within 60 parsecs, but all appear single (*Riaz and Gizis*, in preparation). Taken at face value, this result ($f_{bin} < 6$%) suggests that halo VLM doubles with separations in the range 5-100 AU are rarer than those in the disk population. However, given the danger of unknown selection biases, the possibility of metallicity effects, and the still small numbers of the empirical sample, this result should be taken with caution.

The current data also support the possibility that environment may play a role in the multiple properties of VLM systems. The three young, widely-separated binaries discussed above all reside in loose associations that have average stellar densities of 0.01–1 pc^{-3} (e.g., *Luhman*, 2004; *Mamajek*, 2005), too low for stellar encounters to have a significant disruptive effect (*Weinberg et al.*, 1987). This is in contrast to high-density star formation regions such as Orion, where average densities of 10^4 pc^{-3} (*Hillenbrand*, 1997) are sufficient for stellar encounters to disrupt ~10 AU VLM binaries over a ~10 Myr timescale (*Weinberg et al.*, 1987; *Burgasser et al.*, 2003). The influence of stellar density has been cited for observed differences in multiplicity among solar-mass stars in various clusters (e.g., *Ghez et al.*, 1993; *Scally et al.*, 1999; *Patience and Duchêne*, 2001; *Lada and Lada*, 2003; also see chapter by Duchêne et al.), so differences among VLM binaries should not be surprising. This scenario can also explain the paucity of wide binaries in the field. Dense embedded clusters, in which wide binaries can be easily disrupted (cf., *Kroupa*, 1995a,b,c) contribute perhaps 70–80% of the stars in the Galaxy (*Lada and Lada*, 2003). The few wide systems created in less dense clusters or associations would therefore comprise a negligible fraction of all VLM binaries in the field (cf., *Kroupa and Bouvier*, 2003). This scenario is compelling, but requires better statistics to be tested sufficiently.

3. CONFRONTING THE MODELS

With a full analysis of the empirical properties of VLM multiple systems in hand, we now examine how the predictions of current star and brown dwarf formation theories compare. Detailed discussion on the current modelling efforts are provided in the chapters of Ballesteros-Paredes et al., Bate et al., Goodwin et al., Klein et al. and Whitworth et al. Comparison of formation theories with the general properties (mass function, disk fraction, etc.) of low mass stars and brown dwarfs are provided in the chapters of Duchêne et al. and Luhman et al. Here we focus primarily on the predictions for VLM multiplicity.

3.1 Fragmentation and Dynamical Evolution

Undoubtedly, gravitational contraction of dense cores in molecular clouds provides the fundamental building blocks for stellar and substellar objects. However, the details of the contraction and subsequent evolution of the cores remain critical details under considerable debate. This is particularly the case for VLM star and brown dwarfs whose masses are significantly below the Jeans mass (~1 $M_\odot$), and as such cannot be formed efficiently through basic contraction scenarios (e.g., *Shu et al.*, 1987). The inclusion of additional physics, such as magnetic field effects (*Boss*, 2001, 2002, 2004) and turbulent fragmentation, has brought some resolution to this problem, and has enabled a new generation of VLM formation models.

Turbulent fragmentation (*Henriksen*, 1986, 1991; *Larson*, 1992; *Elmegreen*, 1997, 1999, 2000), in which gas flows collide, are compressed and form gravitationally unstable clumps, has pushed the fragmentation mass limit down to the effective opacity limit, of order 0.01 $M_\odot$ (*Bate et al.*, 2002). *Boyd and Whitworth*, (2005) have modelled the turbulent fragmentation of two dimensional sheets and found a protostellar mass distribution that extends to $\sim 0.003\ M_\odot$. *Padoan and Nordlund* (2004) and *Padoan et al.* (2005) have studied three dimensional turbulent fragmentation of a molecular cloud using an Adaptive Mesh Refinement code, and are also capable of producing cores as small as $\sim 0.003\ M_\odot$. In these studies, no predictions are made on the overall multiplicity of the protostars. However, fragmented cores naturally lead to the creation of gravitationally-bound, high-order multiple systems, as confirmed in multiplicity studies of Class 0 and I protostars (*Haisch et al.*, 2002, 2004; *Reipurth et al.*, 2002, 2004; *Duchêne et al.*, 2004; see chapter by Duchêne et al.), and therefore provide a natural framework for the creation of VLM multiple systems.

However, it is well known that N-body groups are generally dynamically unstable, and dynamical scattering will dissolve such systems in a few crossing times (~10^5 yr), preferentially removing the lowest-mass members (e.g., *Kroupa et al.*, 1999). The scattering of low-mass bodies will also limit the accretion of gas and dust onto initially substellar cores, which would otherwise build up to stellar masses. These ideas have led to the so-called "ejection" model for brown dwarf formation (*Reipurth and Clarke*, 2001), in which brown dwarfs (and presumably VLM stars) are simply stellar embryos ejected from their nascent cloud. This model has received a great deal of attention recently, as its qualitative multiplicity predictions – a small fraction of multiples and a preference for strongly bound binaries (close separations and near-unity mass ratios) – appear to fall in line with observational results.

The most comprehensive simulations of this scenario, incorporating both Smoothed Particle Hydrodynamics (SPH) modelling for fragmentation and accretion and N-body simulations for dynamic interactions, have been produced by M. Bate and collaborators (*Bate et al.*, 2002, 2003; *Bate and Bonnell*, 2005), and are described in detail in the chapter by Bate et al. Their original simulation of a 50 $M_\odot$ cloud produced only one brown dwarf-brown dwarf binary system, still accreting and dynamically unstable at the end of the simulation, implying a VLM binary fraction of $\lesssim 5\%$. It was

immediately recognized that this fraction may be too low when compared to observations (*Close et al.*, 2003). Later simulations (*Bate and Bonnell*, 2005) found that higher VLM binary fractions (up to 8%) were possible in denser clouds. The highest density simulation also produced stable wide (> 60 AU) VLM binary systems when low-mass cores were ejected in the same direction and became bound. It is important to note that the two wide young VLM systems currently known are, on the contrary, associated with *low-density* associations.

While the *Bate et al.* simulations have provided a great leap forward in the modelling of low mass star formation, their relevance to the observed properties of VLM binaries are hindered by necessary computational approximations. First, sink particles encompassing all bound gas within 5 AU are used when densities exceed 10^{-11} g cm^{-3}. This approximation rules out any binaries more closely separated than this limit, encompassing a majority of VLM systems (see §2.2.2). Second, a softened Newtonian potential is employed below separations of 5 AU (down to 1 AU), which enhances the disruption of binary pairs with smaller separations (*Delgado-Donate et al.*, 2004). Again, as the peak of the observed VLM binary separation distribution falls within this range, it is possible that the Bate et al. simulations underpredict the number of VLM binary systems. Because the simulations are computationally expensive, only one simulation is undertaken for a given set of initial conditions, resulting in poor statistics. In addition, the simulations are allowed to run for a limited time ($\sim$0.3 Myr), so long term evolution of unstable multiples is left unresolved.

More recent SPH + N-body simulations have attempted to tackle these issues by reducing the scale of the simulation. Studies by *Delgado-Donate et al.* (2004) and *Goodwin et al.* (2004a,b) have focused on smaller clouds ($\sim 5\ M_\odot$) and have performed multiple simulations to improve statistical results. The *Delgado-Donate et al.* simulations were based on the same format as the Bate et al. work and proceeded in two steps; first an SPH + N-body simulation of the gas and sink particles was conducted for $\sim$0.5 Myr, followed by an N-body simulation of the resulting protostellar cores for a subsequent 10 Myr. This allows an examination of both early fragmentation and accretion on the formation and disruption of bound systems, and the dynamical relaxation of high-order multiples over time. While brown dwarfs were frequently found in multiple systems containing more massive stellar components, particularly at early times ($\sim$1 Myr), none of the simulations produced purely VLM binaries, again indicating a disagreement between theory (or at least the modelling of the theory) and observations. A strong trend of binary fraction with primary mass is found, although this trend is perhaps too strong (underestimating VLM multiplicity and overestimating stellar multiplicity). The SPH simulations of *Goodwin et al.* (2004a,b), which tested variations of the cloud's initial turbulent energy spectrum, also failed to produce any VLM binaries within 0.3 Myr. In retrospect, both sets of simulations may be hindered by their use of 5 AU sink particles and softened Newtonian potentials, and both groups have intentions to address these limitations (M. Bate, private communication).

Pure N-body simulations have focused on the dynamical evolution of small-N clusters of protostars, and (because they are less computationally intensive) have generally produced more robust statistical predictions for VLM multiples than SPH simulations. *Sterzik and Durisen* (2003) simulated the dynamical interactions of closely-separated, small-N clusters and were able to broadly reproduce the empirical trends, including an increasing binary fraction and median separation with increasing primary mass (cf. Fig. 6), a brown dwarf binary fraction of $\sim$10%, and a median VLM binary separation of 3 AU. *Umbreit et al.* (2005) studied the decay of widely-separated accreting triple systems (incorporating momentum transfer with N-body dynamics) and found that VLM systems hundreds of AU apart were efficiently hardened to a distribution of that peaks at 3 AU, with a long tail to wider separations. These simulations predict few very tight brown dwarf binary systems, although this may be because dissipative forces were not included. One drawback to both of these studies is that they do not take into account interactions with the larger star-forming environment, which appear to be important in the SPH simulations of, e.g., *Bate et al.* There are plans to study these effects in detail (S. Umbreit, private communication).

In short, dynamical simulations appear to reproduce many of the observed properties of VLM binaries, both in terms of quantitative results (binary fraction and separation distribution) and overall trends (mass dependence on binary fraction and mean separations). SPH + N-body simulations, on the other hand, generally underpredict the number of VLM binaries, and the lack of statistics makes the assessment of other multiple properties difficult to verify. The shortcomings of SPH simulations are likely related to the use of large sink particles. Decreasing the size of these sink particles, and the imposed smooth potential for close interactions, should be a priority.

3.2 Other Formation Mechanisms

For completeness, we briefly touch upon two other modes of star formation that may be relevant to the creation of VLM multiples. Disk fragmentation can occur when gravitational instabilities in massive circumstellar disks form, either through dynamical interactions with a passing bare star or another disk, or spontaneously through tidal or spiral instabilities. Most disk fragmentation simulations use SPH codes to test the outcomes of different encounter geometries, with results depending largely on the alignment of the angular momentum axes of the interacting pair. The simulations of *Lin et al.* (1998); *Watkins et al.* (1998a,b); and *Boss* (2000) have all successfully produced substellar mass objects through this process (the simulations of *Bate et al.* have also produced protostellar cores through disk interactions). However, the disk mass necessary to produce such objects is nearly $0.1\ M_\odot$, and is hence unlikely around

a VLM primary. Therefore, while the disk fragmentation scenario appears quite capable of producing single brown dwarfs from disks around massive stars, it does little to explain the production of VLM binary systems.

Another VLM formation mechanism recently explored by *Whitworth and Zinnecker* (2004) is photo-evaporation. This process occurs when a substantial prestellar core (a few 0.1 $M_\odot$) is compressed and stripped by the ionizing radiation front of a nearby massive O or B star. *Whitworth and Zinnecker* (2004) do not discuss binary formation explicitly, but is possible in principle if the initial core was fragmented. This scenario also requires the presence of massive young stars, making it appropriate for high-mass star formation environments such as Orion, but not for low-mass environments such as Taurus or Cha I. Therefore, photoevaporation cannot be a universal mechanism for VLM multiple formation.

4. FUTURE OBSERVATIONAL DIRECTIONS

Despite the the large assemblage of VLM binaries now in place (Table 1), it should be clear that the search for VLM binaries should continue, particularly by broadening the multiplicity parameter space sampled. As such, search efforts should focus on low mass ratio systems ($q \lesssim 0.5$), particularly in the field; very tight systems ($\Delta \lesssim 3$ AU); and very wide systems ($\Delta \gtrsim 150$ AU) with moderate to low mass ratios ($q \lesssim 0.8$).

High resolution imaging will remain an important tool in the discovery and characterization of VLM binaries, particularly with the implementation of laser guide star (LGS) AO systems on 5-10 m class telescopes (e.g., Palomar, Keck, VLT). LGS AO greatly increases the number of VLM systems that are accessible from the ground. Ground-based AO enables the examination of larger samples in the field and in nearby moving groups and young star forming regions; and the ability to astrometrically monitor systems on decadal time periods, long after HST is decommissioned. Future studies combining AO imaging with spectroscopy will permit refined characterization of VLM binary components; note that most of the systems listed in Table 1 lack resolved spectroscopy. AO plus coronagraphy, the latter used successfully to identify several VLM companions to nearby, more massive stars (e.g., *Oppenheimer et al.*, 2001, *Lowrance et al.*, 2005) will facilitate the detection of low mass ratio systems around VLM primaries, probing well into the so-called "planetary mass" regime.

For the tightest binaries, high resolution spectroscopy remains an important tool for search and characterization. Efforts thus far have been largely conducted at optical wavelengths. While suitable for young brown dwarfs with M spectral types, optical spectroscopy becomes increasingly limited for L dwarfs, T dwarfs and cooler objects which are extremely faint at these wavelengths. Hence, future studies should focus their efforts using high-throughput, high-resolution infrared spectrographs (e.g., *Simon and Prato*, 2004). Short- and long-term spectroscopic monitoring campaigns of VLM samples should be pursued to identify sufficiently complete samples and to determine systemic properties. Of the few RV variable VLM binary candidates identified to date (*Guenther and Wuchterl*, 2003; *Kenyon et al.*, 2005; *Joergens*, 2006), most have only 2–4 epochs of observation, and parameters such as separation, mass ratio, etc., remain largely unknown. Combining astrometric monitoring with spectroscopic monitoring for closely-separated resolved systems (e.g., Gliese 569Bab; *Zapatero Osorio et al.*, 2004) will permit precise orbital solutions, leading to component mass and semimajor axis measurements, and enabling the examination of other multiplicity properties such as eccentricity distributions and spin/orbit angular momentum alignment.

Tight binaries can also be probed by searches for eclipsing systems. For substellar objects, this is a particularly powerful technique, as the near-constancy of evolved (i.e., field) brown dwarf radii over a broad range of masses (*Burrows and Liebert*, 1993) implies that eclipse depths for edge-on geometries depend only on the relative fluxes of the components, while grazing transits can span a larger range of inclinations for a given separation. To date, only one eclipsing substellar system has been identified in the ~1 Myr ONC, 2MASS J0535218-054608 (*Stassun et al.*, 2006). To the best of our knowledge no large surveys for eclipsing field VLM binaries have been undertaken. While eclipsing systems will likely be rare, the success and scientific yield of transiting extrasolar planet searches (e.g., *Charbonnaeu et al.*, 2000) should inspire dedicated programs in this direction.

Interferometric observations can also probe tighter binaries than direct imaging, encouraging studies in this direction. Current facilities (e.g., Palomar, Keck, VLT) are limited in sensitivity, however; only the closest mid-type M dwarfs have been observed thus far (*Lane et al.*, 2001a; *Segransan et al.*, 2003). Increasing the throughput of these systems, or making use of future space-based facilities (e.g., SIM, TPF-I), may eventually make interferometry a viable observational method in the VLM regíme.

For widely-separated VLM companions, the most extensive limits to date arise from the shallow, wide-field surveys from which most of these objects were identified (e.g., 2MASS, DENIS and SDSS). Only a few dedicated wide-field programs are now underway (*Billères et al.*, 2005; *Allen et al.* in preparation). Deep, but not necessarily high resolution imaging surveys around large samples of VLM primaries would provide better constraints on the frequency and properties of such systems. Such surveys will benefit from proper motion analysis and component spectroscopy, allowing bona-fide systems to be extracted from the vast number of unrelated projected doubles. Searches for wide companions to young nearby stars have identified a few very low mass objects (e.g., *Chauvin et al.*, 2005b; *Neuhäuser et al.*, 2005), and the case of 2MASS 1207-3934AB proves that widely separated low mass companions can exist around VLM primaries. Future searches for equivalent systems, particularly in the field, will test the ve-

racity of the apparent wide-separation desert.

Finally, careful selection of binary search samples should be of high priority. Current imaging and spectroscopic field samples are largely based on compilations from magnitude-limited surveys, and are therefore inherently biased. The examination of *volume-limited* VLM samples (e.g., *Cruz et al.*, 2002) is necessary to eliminate these biases. Similarly, many cluster binary surveys fail to concurrently verify cluster membership, leading to contamination issues (e.g., CFHT-Pl-18; *Martín et al.*, 1998, 2000a). Studies have begun to address this (e.g., *Luhman*, 2004), but more work is needed. Finally, given the suggestion of age and/or environmental effects in binary properties, comparison of large, complete samples for several clusters of different ages will probe the origins of multiplicity properties and over what timescales VLM binaries evolve.

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TABLE 1

KNOWN VERY LOW MASS BINARIES

Source Name	Separation (mas)	Separation (AU)	Spectral Types	Estimated Masses ($M_{\odot}$)	Estimated Masses ($M_{\odot}$)	q	Estimated Period (yr)	Age (Myr)	Association or Note	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Cha Hα8	· · ·	· · ·	M6.5 + [M6.5:]	0.070	· · ·	· · ·	· · ·	2	Cha I; RV	37
2MASS J0253202+271333AB	· · ·	· · ·	M8 + [M8:]	0.092	0.092:	1:	· · ·	· · ·	SB2	8; 42
2MASS J0952219-192431AB	· · ·	· · ·	M7 + [M7:]	0.098	0.098:	1:	· · ·	· · ·	SB2	8; 43
LHS 292AB	· · ·	· · ·	M7 + [M7:]	0.098	0.098:	1:	· · ·	· · ·	SB2	8,28; 76
2MASS J2113029-100941AB	· · ·	· · ·	M6 + [M6:]	0.085	0.085:	1:	· · ·	· · ·	SB2	28; 42
PPl 15AB	· · ·	0.03[a]	M7 + [M8:]	0.070[a]	0.060[a]	0.86	0.0159[a]	120	Pleiades; SB2	1; 47,60
2MASS J0535218-054608AB	· · ·	0.04[b]	M6.5 + [M6.5]	0.054[b]	0.034[b]	0.63	0.0268[b]	1	Orion; SB2, EB	79
2MASS J15344984-2952274AB	65	0.9	T5.5 + [T5.5]	0.035	0.035	1.00	4	· · ·		5; 38
GJ 569BC	103	0.90[a]	M8.5 + M9.0	0.071[a]	0.054[a]	0.76	2.4[a]	300	Ursa Major; triple	2; 3,33,75,49
GJ 1001BC	87	1.0	L4.5 + [L4.5]	0.068	0.068	1.00	4	· · ·	triple	25; 35,36,52
LP 349-25AB	125	1.3	M8 + [M9]	0.090	0.085	0.94	4	· · ·		31; 42
SDSS J092615.38+584720.9AB	70	1.4	T4.5 + [T4.5]	0.050	0.050	1.00	7	· · ·		69; 71
GJ 417BC	70	1.5	L4.5 + [L6]	0.073	0.070	0.96	7	· · ·	triple	4; 39,40
2MASS J0920122+351742AB	70	1.5	L6.5 + [T:]	0.068	0.068	1.00	6	· · ·		7; 39,69,78
2MASS J2252107-173014AB	140	1.9	L6 + [T2]	0.070	0.060	0.86	10	· · ·		32; 58,59
2MASS J1847034+552243AB	82	1.9	M7 + [M7.5]	0.098	0.094	0.96	8	· · ·		23; 43
2MASS J0652307+471034AB	170	2.0	L3.5 + [L6.5]	0.075	0.071	0.95	10	· · ·		78; 43
DENIS PJ035726.9-441730AB	98	2.2	M9.5 + [L1.5]	0.085	0.080	0.91	11	· · ·		4,13
HD 130948BC	134	2.4	L4 + [L4]	0.070	0.060	0.86	14	· · ·	triple	6; 26,40
SDSS J042348.57-041403.5AB	164	2.5	L7 + T2	0.060	0.050	0.83	16	· · ·		68; 43,70,71
2MASS J0746425+200032AB	220	2.5[a]	L0 + L1.5	0.085[a]	0.066[a]	0.78	11[a]	300		4,7,17; 20,39,41,61,71
ϵ IndiBC	732	2.6	T1 + T6	0.045	0.027	0.60	22	1300	triple	16; 40
2MASS J1430436+291541AB	88	2.6	L2 + [L2:]	0.076	0.075	0.99	15	· · ·		4; 43,86?
2MASS J1728114+394859AB	131	2.7	L7 + [L8]	0.069	0.066	0.96	16	· · ·		4,13; 39
LP 213-68AB	122	2.8	M8 + [L0]	0.092	0.084	0.91	15	· · ·	triple	17,53
LHS 2397aAB	207	3.0	M8 + [L7.5]	0.090	0.068	0.76	18	· · ·		10; 36,42,82
LSPM 1735+2634AB	290	3.2	[M9:] + [M9:]	0.082	0.074	0.90	14	· · ·		51; 83
LHS 1070BC	446	3.4[a]	M8.5 + [M9]	0.070[a]	0.068[a]	0.97	16[a]	· · ·	quadruple	18; 74
2MASS J0856479+223518AB[c]	98	3.4	L3: + [L:]	0.071	0.064	0.90	24	· · ·		4; 43
2MASS J1017075+130839AB	104	3.4	L2 + [L2]	0.076	0.076	1.00	23	· · ·		4; 43,86
SDSS 2335583-001304AB	57	3.5	L1: + [L4:]	0.079	0.074	0.94	24	· · ·		4; 81
2MASS J1600054+170832AB	57	3.5	L1 + [L3]	0.078	0.075	0.96	23	· · ·		4,13; 39
LP 415-20AB	119	3.6	M7 + [M9.5]	0.095	0.079	0.83	22	625	Hyades	9; 42
2MASS J12255432-2739466AB	282	3.8	T6 + [T8]	0.033	0.024	0.73	43	· · ·		5; 38,77
SDSS J153417.05+161546.1AB	106	3.8	T1.5 + [T5.5]	0.050	0.040	0.80	35	· · ·		15
SDSS J102109.69-030420.1AB	160	3.9	T1 + T5	0.060	0.050	0.83	33	· · ·		69; 70,72
2MASS J1426316+155701AB	152	4.0	M8.5 + [L1]	0.088	0.076	0.86	27	· · ·		17; 42
2MASS J2140293+162518AB	155	4.0	M8.5 + [L2]	0.092	0.078	0.85	27	· · ·		17; 42
2MASS J15530228+1532369AB	340	4.4	T7 + [T7]	0.040	0.030	0.75	49	· · ·		69; 73
2MASS J1239272+551537AB	211	4.5	L5 + [L5]	0.071	0.071	1.00	35	· · ·		4,13; 39
2MASS J2206228-204705AB	168	4.5	M8 + [M8]	0.092	0.091	0.99	31	· · ·		17; 42
2MASS J0850359+105716AB	160	4.7	L6 + [L8]	0.050	0.040	0.80	39	· · ·		7; 41,52,70
2MASS J1750129+442404AB	158	4.9	M7.5 + [L0]	0.095	0.084	0.88	36	· · ·		9; 42
USco-109AB[c]	34	4.9	M6 + [M7.5]	0.070	0.040	0.57	46	5	Up Sco	29; 45,65
2MASS J2101154+175658AB	234	5.4	L7 + [L8]	0.068	0.065	0.96	49	· · ·		4,13; 39
Kelu-1AB	291	5.4	L2 + [L4]	0.060	0.055	0.92	52	· · ·		24; 41,52
2MASS J0429184-312356AB	531	5.8	M7.5 + [L1]	0.094	0.079	0.84	48	· · ·		23,78; 43
2MASS J0147328-495448AB	190	5.8	M8 + [M9]	0.086	0.080	0.93	47	· · ·		78
2MASS J2152260+093757AB	250	6.0	L6: + [L6:]	0.069	0.069	1.00	55	· · ·		78
MHO Tau 8AB	44	6.2	M6 + [M6.5]	0.100	0.070	0.70	53	2	Taurus	55; 56
DENIS J122815.2-154733AB	275	6.4[a]	L6 + [L6]	0.065[a]	0.065[a]	1.00	44[a]	· · ·		11; 41,64,71
DENIS J100428.3-114648AB	146	6.8	L0: + [L2:]	0.080	0.076	0.95	63	· · ·		4
2MASS J2147436+143131AB	322	7.0	M8 + [L0]	0.084	0.078	0.93	65	· · ·		4,13; 42
DENIS J185950.9-370632AB	60	7.7	L0 + [L3]	0.084	0.076	0.90	76	5	R-CrA	20; 57
2MASS J1311391+803222AB	267	7.7	M8.5 + [M9]	0.089	0.087	0.98	72	· · ·		17; 42
IPMBD 29AB	58	7.8	L1 + [L4]	0.045	0.038	0.84	106	120	Pleiades	14; 47
2MASS J1146345+223053AB	290	7.9	L3 + [L4]	0.055	0.055	1.00	94	· · ·		7,12; 41,52
CFHT-Pl-12AB	62	8.3	M8 + [L4]	0.054	0.038	0.70	111	120	Pleiades	14; 47,62
2MASS J1127534+741107AB	246	8.4	M8 + [M9]	0.092	0.087	0.95	80	· · ·		17; 42
2MASS J1449378+235537AB	134	8.5	L0 + [L3]	0.084	0.075	0.89	88	· · ·		4,13; 39
LP 475-855AB	294	8.5	M7.5 + [M9.5]	0.091	0.080	0.88	85	625	Hyades	9; 42
DENIS J020529.0-115925AB	510	9.2	L7 + [L7]	0.070	0.070	1.00	105	· · ·	poss. triple	12; 52,41

TABLE 1—*Continued*

Source Name	Separation		Spectral Types	Estimated Masses		q	Estimated Period	Age	Association or Note	Ref.
	(mas)	(AU)		($M_\odot$)	($M_\odot$)		(yr)	(Myr)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
USco-66AB	70	10.2	M6 + [M6]	0.070	0.070	1.00	120	5	Up Sco	29; 45,65
2MASS J17072343-0558249AB	950	10.4	M9 + L3	0.090	0.060	0.67	125	· · ·		67
GJ 337CD	530	10.9	L8 + [T:]	0.055	0.055	1.00	150	· · ·	quadruple	30; 50,67
2MASS J0915341+042204AB	730	11.0	L7 + [L7]	0.070	0.070	1.00	138	· · ·		78
IPMBD 25AB	94	12.6	M7 + [L4]	0.063	0.039	0.62	200	120	Pleiades	14; 47
DENIS J144137.3-094559AB	420	14.3	L1 + [L1]	0.072	0.072	1.00	200	· · ·	triple	4,48; 39,80
2MASS J2331016-040618AB	573	15.0	M8 + [L7]	0.093	0.067	0.72	200	· · ·	triple	4,13,17; 42,49
USco-55AB	122	17.7	M5.5 + [M6]	0.100	0.070	0.70	250	5	Up Sco	29; 45,65
CFHT-Pl-18AB	330	34.6	M8 + M8	0.090	0.090	1.00	680	· · ·		4; 19
DENIS J220002.0-303832.9AB	1090	38.2	M8 + L0	0.085	0.083	0.98	800	· · ·		66
2MASS J1207334-393254AB	776	41.1	M8.5 + L:	0.024	0.004	0.17	2 250	8	TW Hyd	22,63; 34
DENIS J055146.0-443412.2AB	2200	220.0	M8.5 + L0	0.085	0.079	0.93	11 500	· · ·		27
2MASS J11011926-7732383AB	1440	241.9	M7 + M8	0.050	0.025	0.50	20 000	2	Cha I	21; 44

NOTE.—Uncertain values are indicated by colons. Additional column information: (1) name of binary; (2) angular separation in mas; (3) projected separation (Δ) in AU, or semimajor axis of orbit as noted; (4) spectral types of binary components; for sources without resolved spectroscopy, primary spectral type is for combined light data, secondary spectral type is estimated from photometric flux ratios (as indicated by brackets); (5) estimated primary mass in $M_\odot$, taken as the average of the reported mass ranges; masses determined from orbital dynamics are indicated; (6) estimated secondary mass in $M_\odot$, taken as the average of the reported mass ranges; masses determined from orbital dynamics are indicated; (7) $q \equiv M_2/M_1$, as reported or calculated from columns [5]-[6]; (8) estimated orbital period in yr, assuming circular orbit with semimajor axis $a = 1.26\Delta$ (FM92); sources with period measurements from orbital measurements are indicated; (9) estimated age in Myr of binary if member of a moving group or association, or companion to a age-dated star; (10) additional notes, including cluster association; (11) references as given below; discovery references are listed first, followed by references for additional data (spectral types, distance measurements/estimates, orbital measurements) separated by a semicolon.

[a] Parameters derived or estimated from orbital motion measurements.

[a] Parameters for 2MASS J0535218-054608AB based on both spectroscopic orbit and eclipsing light curve; see *Stassun et al.* (2006).

[c] Candidate binary.

References. — (1) *Basri and Martín* (1999); (2) *Martín et al.* (2000b); (3) *Lane et al.* (2001b); (4) *Bouy et al.* (2003); (5) *Burgasser et al.* (2003); (6) *Potter et al.* (2002); (7) *Reid et al.* (2001); (8) *Reid et al.* (2002b); (9) *Siegler et al.* (2003); (10) *Freed et al.* (2003); (11) *Martín et al.* (1999); (12) *Koerner et al.* (1999); (13) *Gizis et al.* (2003); (14) *Martín et al.* (2003); (15) *Liu et al.* (in preparation); (16) *McCaughrean et al.* (2004); (17) *Close et al.* (2003); (18) *Leinert et al.* (2001); (19) *Martín et al.* (2000a); (20) *Bouy et al.* (2004b); (21) *Luhman* (2004); (22) *Chauvin et al.* (2004); (23) *Siegler et al.* (2005); (24) *Liu and Leggett* (2005); (25) *Golimowski et al.* (2004); (26) *Goto et al.* (2002); (27) *Billères et al.* (2005); (28) *Guenther and Wuchterl* (2003); (29) *Kraus et al.* (2005); (30) *Burgasser et al.* (2005a); (31) *Forveille et al.* (2005); (32) *Reid et al.* (2006); (33) *Kenworthy et al.* (2001); (34) *Mamajek* (2005); (35) *Leggett et al.* (2002); (36) *van Altena et al.* (1995); (37) *Joergens* (2006); (38) *Tinney et al.* (2003); (39) *Kirkpatrick et al.* (2000); (40) *Perryman* (1997); (41) *Dahn et al.* (2002); (42) *Gizis et al.* (2000b); (43) *Cruz et al.* (2003); (44) *Whittet et al.* (1997); (45) *de Zeeuw et al.* (1999); (46) *Kenyon et al.* (1994); (47) *Percival et al.* (2005); (48) *Stephens et al.* (2001); (50) *Wilson et al.* (2001); (51) *Law et al.* (2006); (52) *Kirkpatrick et al.* (1999); (53) *Gizis et al.* (2000a); (54) *Delfosse et al.* (1997); (55) *White et al.* (in preparation); (56) *Briceño et al.* (1998); (57) *Casey et al.* (1998); (58) *Kendall et al.* (2004); (59) *McGovern* (2005); (60) *Martín et al.* (1996); (61) *Bouy et al.* (2004a); (62) *Stauffer et al.* (1998); (63) *Chauvin et al.* (2005a); (64) *Brandner et al.*, 2004; (65) *Ardila et al.* (2000); (66) *Burgasser and McElwain* (2006); (67) *McElwain and Burgasser* (in preparation); (68) *Burgasser et al.* (2005b), (69) *Burgasser et al.* (in preparation); (70) *Vrba et al.* (2004); (71) *Geballe et al.* (2002); (72) *McLean et al.* (2003); (73) *Burgasser et al.* (2002); (74) *Leinert et al.* (2000); (75) *Zapatero-Osorio et al.* (2004); (76) *Dahn et al.* (1986); (77) *Burgasser et al.* (1999); (78) *Reid et al.* (in preparation); (79) *Stassun et al.* (2006); (80) *Seifahrt et al.* (2005); (81) *H. Bouy*, private communication (2005); (82) *Tinney* (1996); (83) *Lépine and Shara* (2005)